doi:10.1038/nature13031

1 Summary

Here, we summarise briefly the key points demonstrated in the supplementary information. Full details regarding the analysis performed for the quadruply imaged quasar 1RXS J113151.6-123158 (hereafter RX J1131-1231) are given in the following sections.

A: The spin measurements with *Chandra* are found to be consistent for a variety of analysis techniques: We demonstrate the presence of residuals to the standard powerlaw AGN continuum consistent with the soft excess commonly observed in local, unobscured Seyfert galaxies, and also with a relativistically broadened iron emission line, from which the spin of the black hole can be constrained. We do so first using a phenomenological model including a relativistic line profile, and then with a fully physically self-consistent reflection model, comparing the results obtained with a time-averaged and time-resolved analyses of the data from individual *Chandra* images. The spin constraints obtained with these various analyses are all found to be consistent, implying a rapidly rotating black hole.

B: Spin determination is consistent for both *XMM-Newton* and *Chandra*: Having demonstrated the consistency of the results obtained with the individual *Chandra* images, we then constrain the spin of RX J1131-1231 using all the selected *Chandra* data simultaneously with the self-consistent reflection model, and obtain $a = 0.90^{+0.07}_{-0.15}$ at 3σ confidence. We also constrain the spin in the same manner with an independent *XMM-Newton* observation, obtaining $a = 0.64^{+0.33}_{-0.14}$ (again, 3σ confidence), fully consistent with the *Chandra* constraint. Finally, modeling both the *Chandra* and *XMM-Newton* datasets simultaneously in order to obtain the most robust measurement, we constrain the spin of RX J1131-1231 to be $a = 0.87^{+0.08}_{-0.15}$ at the 3σ level of confidence.

C: The spin measurements are robust against absorption: Lastly, we consider whether there is any evidence for absorption by partially ionised material, often seen in local Seyferts and other quasars, in the spectrum of RX J1131-1231, and investigate any effect this might have on the spin constraint obtained. Through phenomenological modelling, we show that although ionised absorption could plausibly reproduce the soft excess, a relativistic iron emission line is still required, and a high spin is again obtained. Furthermore, when considering the self-consistent reflection model, which includes the soft emission lines that naturally accompany the iron emission, the addition of ionised absorption to the model does not improve the fit, and the spin constraint obtained again remains unchanged.

2 Background and Representative Values for 1RXS J113151.6-123158 (RX J1131-1231)

- Mass in the range of $\sim 8 \times 10^7$ $\mathrm{M}_\odot$ (via Hβ line[18]) to $M_{BH} \sim 2 \times 10^8$ $\mathrm{M}_\odot$ (via MgII line). However, the value for the dimensionless spin parameter presented in this work does not depend on the mass of the black hole.
- Quasar[19] at $z = 0.658$, lensing galaxy at at $z = 0.295$.
- Intrinsic (non magnified) bolometric luminosity $\log_{10}\mathrm{L_{Bol}} \approx 45\,\mathrm{erg\ s^{-1}}$ assuming a magnification factor of 11.6 and a bolometric correction of 9.6 for image B. See [18] for details.

The time-averaged, unabsorbed fluxes (observed frame) based on the co-added spectrum described in §3 are listed below. Note that the last two fluxes are obtained using the extrapolation of the best fit *Baseline-reflection* model (see below), and are only illustrative.

- $F_{(2-10\mathrm{keV})} = (7.92 \pm 0.15) \times 10^{-13}\,\mathrm{erg\ cm^{-2}\ s^{-1}}$.
- $F_{(0.3-10\mathrm{keV})} = (1.45 \pm 0.06) \times 10^{-12}\,\mathrm{erg\ cm^{-2}\ s^{-1}}$.
- $F_{(0.3-100\mathrm{keV})} = (3.37 \pm 0.23) \times 10^{-12}\,\mathrm{erg\ cm^{-2}\ s^{-1}}$.
- $F_{(10-40\mathrm{keV})} = (1.21 \pm 0.09) \times 10^{-12}\,\mathrm{erg\ cm^{-2}\ s^{-1}}$.

Throughout the text, we utilize 2 models to describe the observed X-ray spectrum, which may be described in XSPEC as follows:

- *Baseline-simple*: PHABS $\times$ (ZPHABS $\times$ (ZPOWERLAW + DISKBB + RELLINE))
- *Baseline-reflection*: PHABS $\times$ (ZPHABS $\times$ (ZPOWERLAW + RELCONV $\otimes$ REFLIONX)),

where $\times$ and $\otimes$ indicate multiplication and convolution respectively.

Optical studies[20] have established the size of the optical disk in RX J1131-1231 to the order of $100r_\mathrm{g}$. Microlensing studies in X-rays have subsequently constrained the size[16,20,31] of the X-ray emitting region to $\lesssim 10r_\mathrm{g}$. As the accretion disk around a supermassive black hole emits mostly in optical/UV, the X-ray emitting region constrained by these studies to be $\lesssim 10r_\mathrm{g}$ is traditionally associated with the corona. However, we show in this work that at least part of this emission is due to reprocessed X-rays in the innermost regions around the black hole. Thus, the $\sim 10r_\mathrm{g}$ upper limit found in microlensing studies is likely to be characteristic of the size of the reprocessing region[21], with the corona actually limited to a region $\ll 10r_\mathrm{g}$.

All calculations in this paper assume a flat ΛCDM cosmology with $H_o = 70\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\Omega_{vac} = 0.73$ and $\Omega_M = 0.27$. All figures in this manuscript are shown in the observed frame.

3 Toward Black Hole Spin: Chandra

Due to the lensed nature of this source we are afforded a remarkable number of observations of the quasar despite a modest number of pointings. Ref[41] estimated the time delay between images B and C to be at most ≈ 0.3 days and the delay between B and D to be between $\approx 90 - 96$ days. As such, each of the 30 individual pointings effectively provides up to 4 spectra probing different epochs. In order to account for possible intrinsic variability present in the large number of spectra of RX J1131-1231, we proceed by modelling the various spectra using similar methodologies to those often employed in the analyses of X-ray binaries where large sets of pointed observations are available (see e.g. ref[42]).

As discussed thoroughly in[16], the variability of Images-B and C through all the epochs are thought to be closely related to the intrinsic variability of the quasar. Those authors estimate that the intrinsic variability of the quasar should be no larger than 28%. Images A and D on the other hand display a high level of variability which is attributed to microlensing. In the following, we fit all 27 epochs of Image-B with a physically motivated model.

3.1. Fits with phenomenological models: *Baseline-simple*

3.1.1. Individual image-B spectra: We start by confirming the presence of the soft-excess and possible residuals around the iron line region for all 27 spectra of image-B. We do this again in a phenomenological manner by using the *baseline-simple* model, allowing only the normalisations of the various components as well as the power-law indices to vary between each epochs. We again constrain the rest frame energy of the relativistic line to the 6.4-6.97 keV range and for simplicity assume that this is not varying between epochs. Extended Data Fig. 1 (a) shows the best fit ($\chi^2/\nu = 2207.2/2172 = 1.02$) models for the simultaneous fit of all 27 observations. On the right, we again remove the DISKBB and line component to emphasise the presence of the soft-excess and the iron line. We also show over-plotted on the data in Extended Data Fig. 1 (b), the ratio between the total model and the illuminating power-law for the spectrum of epoch-23. Replacing the relativistic line with a simple Gaussian profile with energies constrained in a similar manner to RelLine and again allowing the normalisation to vary between epoch, resulted in a worse fit ($\Delta\chi^2 = +32.9$ for two fewer degrees of freedom) compared to the *baseline-simple* model.

When using the *baseline-simple* model here, we have made the logical assumption that the inner disk inclination (measured with respect to the normal of the disk where 0 and 90 degrees mean face-on and edge-on, respectively) and the black hole spin are not changing. Furthermore, at this early stage in the analysis we have also tied the ionisation state of the disk as well as the disk emissivity profile between the different epochs. With these basic assumptions in mind, the *baseline-simple* model yields a spin and inclination of $a = 0.86^{+0.06}_{-0.08}$ $\mathrm{Jc/GM^2}$ and $\theta = 17^{+8}_{-3}$

degrees respectively (90% confidence), as well as an average emissivity $q > 6.2$ for the image B data. Our results also indicate that there is no large neutral column at the source redshift, with an upper limit based on this model of $N_{\mathrm{H}}(z = 0.658) < 6.5 \times 10^{20}\,\mathrm{cm}^{-2}$. Similar conclusions for the low intrinsic absorption and low inclination were found by ref[16]. We also note that the mean value for the powerlaw index is $\Gamma = 1.61 \pm 0.11$ (s.d.), and we find no *statistically significant* variation in this parameter through all epochs. Similar conclusions regarding the constancy of Γ in Image-B were made by ref[31], where the authors find an average value of ~ 1.68 ranging from $\sim 1.41 - 1.82$ based on the first six epochs (see their Table 3).

We note briefly that despite the increase in the number of spectra from 3, as considered previously when focusing on just epoch 23, to 27 for the full image B dataset, the total degrees of freedom does not increase by a similar factor since the exposures and thus S/N of the various observations are not the same. In fact, ν goes from ~ 405 to ~ 2172, a factor of ~ 5 increase.

3.1.2. Combined "microlensing-quiet" images-B and C: It is common practice in the study of nearby Seyferts to use a single time averaged-spectrum when performing detailed analyses aimed at obtaining the spin parameter; similar to the goal set here. This practice is motivated in large part by either the computational intensity of such tasks or due to low S/N in individual spectra. However, the time averaged result has usually been shown to be consistent with that obtained through more detailed analyses, e.g. time resolved spectroscopy, when it has been possible to assess both. A case in point is the measured spin parameter of NGC 3783 where work has been done on both time resolved and averaged spectra to arrive at similar value for the spin[43,44], using a methodology similar to that employed here.

As detailed in ref[16], Images-A and D are thought to be representative of microlensing "active" states, meaning that the observed variability is largely due to microlensing effects. As microlensing is capable of selectively amplifying different regions depending on their size, it is possible that spectra in the active states are deformed in a complex manner[45,46] unrelated to General relativistic and reprocessing effects from the inner accretion disk[7]. As such, in this section we begin by co-adding the spectra and responses of Images-B and C to form two time-averaged spectra representative of the microlensing "quiet" state. We fit these spectra in the 0.4-8.0 keV range as a conservative precaution, as the lowest energy bins are systematically above any reasonable continuum fit, likely related to known ACIS calibration issues, e.g., see
http://cxc.harvard.edu/ciao4.4/why/acisqecontam.html and
http://cxc.harvard.edu/cal/Acis/Cal_prods/qeDeg/index.html.

Extended Data Fig. 2 (a) shows the co-added spectra of Images-B and C. It is clear from the residuals as well as the poor ${\chi^2}_{\mathrm{B}}/\nu_{\mathrm{B}} = 559.6/358 = 1.56$ and ${\chi^2}_{\mathrm{C}}/\nu_{\mathrm{C}} = 291.6/250 = 1.17$

for B and C respectively, that a simple power-law is not a good representation of the spectra. Adding a DISKBB component for the soft excess again improves both fits (${\chi^2}_{\rm B}/\nu_{\rm B} = 431.0/356 = 1.21$; ${\chi^2}_{\rm C}/\nu_{\rm C} = 262.9/248 = 1.06$) but clear residuals remains above $\sim 2\,\rm keV$. We proceed by adding a relativistic line (RelLine) component again constrained to lie between 6.4 and 6.97 $\rm keV$ and initially having a powerlaw emissivity profile. This improved the fit ($\Delta{\chi^2}_{\rm B}/\Delta\nu_{\rm B} = -27.6/-5$; $\Delta{\chi^2}_{\rm C}/\Delta\nu_{\rm C} = -13.7/-5$). However, there still appeared to be narrow residuals at 3.86 $\rm keV$ (6.4 $\rm keV$ in the rest frame) in both spectra (see bottom panel of Extended Data Fig. 2). This possible emission line could be associated with reflection from distant material as is often found in nearby Seyferts, or it could be coming from the outer parts of the accretion disk. Initially assuming the latter, we change the emissivity profile of RelLine so that within a radius of $10r_{\rm g}$ the emissivity is Q_{in} and beyond this radius it is described as $Q_{out} > 2$. Such a broken powerlaw prescription for the emissivity profile is naturally expected when one suspects the black hole to be rapidly rotating and the corona to be compact[24,47,48]. The break at $10r_{\rm g}$ is motivated both theoretically[47] as well as observationally since this is the likely scale for the X-ray emitting region in RX J1131-1231 as measured using gravitational microlensing[16,20,31]; however, we note that allowing this parameter to be free does not change the results presented here as the break radius is not very well constrained.

This *baseline-simple* model with a broken powerlaw emissivity profile provides a good fit to the time-averaged spectra of both images (${\chi^2}_{\rm B}/\nu_{\rm B} = 393.9/350 = 1.13$; ${\chi^2}_{\rm C}/\nu_{\rm C} = 231.0/242 = 0.95$). With the increased S/N provided by the co-added spectrum, the addition of the relativistic line component is now significant at $> 4.3\sigma$ level of confidence (F-test false alarm probability of 1.9×10^{-5}) for image-B, and at the 4σ level (F-test false alarm probability of 7.4×10^{-5}) for image-C. Extended Data Table 1 summarises the various parameters. Most importantly, the value for the spin found for both images (see Extended Data Fig. 3; black curves) are in excellent agreement with the results found in the previous section for the time-resolved fits of Image-B. The inclination and the power-law index found for image-B are also in excellent agreement with the results for the time-resolved analyses presented in the previous section.

As mentioned previously, a further possibility for the narrow component seen in Extended Data Fig. 2 is emission from distant material. Indeed it is possible that the narrow feature is due to a combination of these two effects, i.e., emission from distant material and a broken emissivity profile. Such a fit combining both a broken emissivity profile with $Q_{out} = 3$ – the expected asymptotic value at large ($\gtrsim 10r_{\rm g}$) distances – together with a Gaussian to characterise distant reflection having a width frozen at $1\,\rm eV$, also provides a satisfactory fit with ${\chi^2}_{\rm B}/\nu_{\rm B} = 400.2/350 = 1.14$ and ${\chi^2}_{\rm C}/\nu_{\rm C} = 231.8/242 = 0.96$. The confidence contour for this model are also shown in Extended Data Fig. 3 (blue curves). All parameters remain essentially unchanged from those presented in Extended Data Table 1.

Before applying the more physically-motivated *baseline-reflection* model to these spectra, it is worth comparing our results for Image-C with those obtained by ref[16]. In their work, they model the co-added spectrum of Image-C with a single power-law ($\Gamma = 1.79 \pm 0.02$) together with a Gaussian at $E_{\mathrm{Ga}} = 6.36^{+0.07}_{-0.08}\,\mathrm{keV}$ (rest frame) having an equivalent width of $EW = 154^{+70}_{-80}\,\mathrm{eV}$. We find that a similar model indeed provides an adequate fit with ${\chi^2}_{\mathrm{C}}/\nu_{\mathrm{C}} = 260.3/247 = 1.05$, $E_{\mathrm{Ga}} = 6.38^{+0.05}_{-0.06}$, $EW = 137\,\mathrm{eV}$, and $\Gamma = 1.76 \pm 0.03$, meaning that all our results for this model are in excellent agreement with their work. Although this model does formally provide an adequate fit to the time-averaged data of Image-C, the addition of a soft component again improves the fit dramatically ($\Delta{\chi^2}_{\mathrm{C}}/\Delta\nu_{\mathrm{C}} = -23.2/-2$) and an F-test shows that this extra component is required at the 4.4σ level (F-test false alarm probability of 1.1×10^{-5}). Although we cannot differentiate between the RelLine + DISKBB model (${\chi^2}_{\mathrm{RelLine}}/\nu_{\mathrm{relLine}} = 231.0/242 = 0.95$) from the Gaussian + DISKBB model (${\chi^2}_{\mathrm{Gaussian}}/\nu_{\mathrm{Gaussian}} = 237.2/245 = 0.97$) on a statistical basis for image-C alone, the presence of the line *together with* the extra soft component is statistically robust and for the various reasons presented throughout this manuscript we favour the relativistic reflection based interpretation for the emission line seen in Image-C.

3.1.3. Combined "microlensing-active" images-A and D: We now consider the two "microlensing-active" images, A and D. Ref[16] highlight two periods of distinct behaviour in the evolution of Image-D, one in which the the Fe-$K\alpha$ line profile appears to show a distinctive peak at $\sim 6.4\,\mathrm{keV}$, which they call Periods 1 and 3 (epochs 1-16 and 23-30 respectively), and the other where the Fe-line region is better described by a double profile during their Period 2 (epochs 17-22). In comparison, they did not see any such evolution from the microlensing-quiet period in Image-C. Extended Data Fig. 2 (b) shows the residuals to a model consisting of a combination of power-law and Gaussian profiles in a similar manner to that of ref[16]. We cannot directly compare our residuals to those of ref[16] since the authors did not show such a figure; however, close inspection of their spectra indicates residuals similar to the ones shown here.

It is clear from the residuals below $\sim 1\,\mathrm{keV}$ shown in Extended Data Fig. 2 (b), that this simple power-law does not provide a good representation of Periods 1 and 3 for either Image-A or D. However, possibly owing to the poor S/N afforded in Period-2, the data is here consistent with a simple power-law and as such we do not consider these data further. The familiar appearance of the soft excess is again well characterised phenomenologically by a DISKBB, and the addition of such a component to the co-added spectrum of Image-D, Period 1+3 yields an improvement of $\Delta{\chi^2}_{\mathrm{D13}}/\Delta\nu_{\mathrm{D13}} = -31.9/-2$ (final ${\chi^2}_{\mathrm{D13}}/\nu_{\mathrm{D13}} = 238.5/242 = 0.99$). Similarly, adding a DISKBB to the corresponding period of Image-A yields ${\chi^2}_{\mathrm{A13}}/\nu_{\mathrm{A13}} = 250.4/267 = 0.94$, an improvement in χ^2 of 58.1 for 2 degrees of freedom. The residuals during Periods-1 and 3 for both Images-A and D closely resemble those of the microlensing-quiet Images B and C (see Extended

Data Fig. 2) and the model we have used to account for the soft excess can again be linked with the clear presence of Fe emission.

3.1.4. Summary of phenomenological (*Baseline-simple*) Results: We have used the *Baseline-simple* model to provide initial constraints on the spectral shape of RX J1131-1231, and to compare the results obtained from the different individual images. First of all, we stress that the soft excess and Fe K residuals present in epoch-23 and detailed above are present in all 27 epochs of Image-B (Extended Data Fig. 1). We find no significant evolution in the powerlaw index as obtained with the *Baseline-simple* model throughout these epochs. The average value is found to be $\Gamma = 1.61 \pm 0.11$ (s.d.). A joint fit to all 27 epochs suggests the lack of any significant absorption at the source redshift, and gives a spin parameter $a = 0.86^{+0.06}_{-0.08}$ (90% significance). Co-adding the spectra of image-B, the soft-excess (modeled with a DISKBB) and the broad iron line are required at $>> 5\sigma$ and $> 4.3\sigma$ respectively, even before the data from images A, C and D are considered.

The co-added spectra of images A, C and D (after excluding the powerlaw dominated Period 2 for images A and D) show similar residuals to a simple powerlaw continuum as the co-added spectrum of Image-B (Extended Data Fig. 2). The spin parameter obtained with the *Baseline-simple* model for image C is fully consistent with that obtained previously for Image-B (See Extended Data Table 1 and Extended Data Fig. 3). Unfortunately, owing to the lower S/N in the co-added spectra from images A and D, these data do not allow for individual spin constraints, but we again stress that similar Fe K residuals to those seen in images B and C are observed.

3.2. Fits with physical models: *Baseline-reflection*: We now proceed to fit the spectra with a self consistent physical model. As mentioned in the main manuscript, the use of a disk blackbody for the soft excess is purely phenomenological, and is only used to model the soft-excess in a similar manner to previous work on quasars for ease of direct comparison (see e.g. [11,12]).

We replace the DISKBB and RelLine components with the reflection model REFLIONX of [49] and account for relativistic affects using the RelConv kernel from[37]. To the best of our knowledge, RelConv (and its equivalent line model RelLine) represent the current state of the art in relativistic reflection modelling. In XSPEC terminology, this combination of components reads:

$$\mathrm{ZPHABS} \times \mathrm{PHABS} \times (\mathrm{ZPOWERLAW} + \mathrm{RelConv} \otimes \mathrm{REFLIONX})$$

where $\otimes$ denotes convolution.

When using REFLIONX, we constrained the power-law index of the reflection component to be that of the illuminating power-law and set its redshift to that of the quasar. The iron abundance is initially frozen at Solar (Fe/solar=1).

3.2.1. Individual image-B spectra: We begin our self-consistent analysis by modeling the 27 spectra from image-B simultaneously. The intrinsic neutral absorbing column, the black hole spin, the accretion disk inclination and the emissivity index are linked between all 27 spectra, i.e. assumed to be constant with time, while the normalisations of REFLIONX and the power-law, the photon index and the disk ionisation were allowed to vary between them.

The *Baseline-reflection* model characterised all the data well ($\chi^2/\nu = 2241.8.6/2174 = 1.03$), including the intrinsic variability, in a self-consistent manner. RX J1131-1231 is thought to be accreting[18] at $L/L_{\rm Edd} \sim 0.07$, – where $L_{\rm Edd}$ is the Eddington limit – which is similar to the accretion rate often observed in a number of Seyferts, including the canonical source for reflection based spin measurements: MCG-6-30-15[8,50–52]. Therefore, it is no surprise that this combination of model works so well for RX J1131-1231.

We show in Extended Data Figure 3 the confidence limits for the spin as obtained from the combined statistics of these 27 observations for a total exposure of $\sim 318\,\mathrm{ks}$. The spin is constrained to $a = 0.90^{+0.08}_{-0.10}$ Jc/GM^2 at the 3σ level of confidence (99.73%). The inclination, emissivity index and intrinsic absorption are constrained to < 19 degrees, $Q = 5.2 \pm 0.3$ and $N_{\rm H} = (1.0^{+0.2}_{-0.1}) \times 10^{21}\,\mathrm{cm}^{-2}$ at the 90% level.

We stress here that the constraint on the spin does not come solely from the iron emission feature, but from the full reflection spectrum, including the featureless soft-excess. Of course another way to obtain a featureless continuum is to have metallicities significantly below the solar value used here. This is highly unlikely as quasars are famously known to have enhanced metallicities [53], with a near flat evolution from $z = 0$ up to $z \sim 4 - 5$, after which it is possible that it declines to solar or even subsolar values[54].

3.2.2. Combined "microlensing-quiet" images-B and C: Following our phenomenological analysis, we now again consider the data from the two "microlensing-quiet" images, B and C. Here, though, we limit our analysis to the co-added spectra obtained from these images, as simultaneously modeling the individual observations of both images would be extremely computationally intensive. As discussed previously, these co-added spectra probe the time averaged features of the system, in an identical manner to that often exploited in nearby Seyferts.

Again we apply the *Baseline-reflection* model to the two combined spectra. A narrow ($1\,\mathrm{eV}$) Gaussian is included at $6.4\,\mathrm{keV}$ and we use a broken emissivity profile with $Q_{out} > 2$. Extended Data Table 1 details the parameters found for this model. The confidence contours for the spin as obtained for each individual Image are also shown in Extended Data Figure 3 (red curves). It is clear from Extended Data Table 1 and Fig. 3 that the parameters between both Images-B and C are all consistent with one another. The consistent shape of Image-C during the full observation was also highlighted by ref[16]. In addition, the spin constraints obtained from each image are consistent with that found previously during our time resolved analysis of image B.

3.2.3. Combined "microlensing-active" images-A and D; Periods 1 and 3: Finally, we consider the "microlensing-active" images (A and D) in the context of the *Baseline-reflection* model. The *exact same* model for the co-added spectrum of Image-B detailed in Extended Data Table 1 gives ${\chi^2}_{\rm A13}/\nu_{\rm A13} = 253.8/274 = 0.93$ when applied to the co-added spectrum from image A and simply renormalised. This is as expected since Images-A and B (and C) are probing similar times. However, as Image-D lags the rest by ~ 100 days, we use the same model as above but allow the various normalisations, inner disk emissivity profile, power-law index and disk ionisation to vary. This again provides an excellent fit to the co-added spectrum of Image-D (${\chi^2}_{\rm D13}/\nu_{\rm D13} = 245.56/243 = 1.01$). All parameters are consistent within errors with those reported in Extended Data Table 1, although we note that the power-law index and the disk ionisation are not particularly well constrained ($\Gamma_{D13} < 2.2$; $\xi_{D13} = 1270^{+1100}_{-950}\,\rm erg\ cm\ s^{-1}$).

3.2.4. Summary of self-consistent (*Baseline-reflection*) results: In addition to our phenomenological analysis, we have also considered the data obtained from the individual *Chandra* images in the context of the physically self-consistent *Baseline-reflection* model. We began by applying this model to the 27 individual spectra of image B simultaneously, and then to the co-added spectra obtained from images B and C. Excellent fits are obtained in each case. The spin constraints (Extended Data Fig. 3) obtained from these analyses are – at the 90% confidence level – $a = 0.90^{+0.04}_{-0.05}\ \rm Jc/GM^2$ (image B, time resolved), $0.92^{+0.04}_{-0.06}$ (image B, co-added) and $0.80^{+0.08}_{-0.06}$ (image C, co-added), which are all consistent with one another. Finally, the *Baseline-reflection* model also provides excellent fits to the co-added spectra from images A and D, and consistent results are again obtained.

4 The Spin of RX J1131-1231

4.1. Combined Chandra data: 1.13 Msec of exposure: We have shown above that the spectral shape of the microlensing quiet images (Images B and C) as well as that for the more active images during certain periods (Images-A and D during periods 1 and 3 of ref[16]) are extremely similar to one another. Following the standard procedure employed in the study of nearby Seyferts, we now combine these observations into a single time-averaged spectrum. This combined spectrum has a total exposure of 1.13 Msec and $\sim 100,000$ counts in the 0.4-8.0 keV range.

4.1.1. Baseline-simple: Extended Data Fig. 4 (a) shows the time-averaged *Chandra* data fit with the *baseline-simple* model. This results in an excellent fit with $\chi^2/\nu = 410.4/408 = 1.006$. The relativistic line at $E_{\rm RelLine} = 6.49^{+0.05}_{-0.04}\,\rm keV$ returns a broken emissivity profile with $Q_{\rm in} = 7.2^{+0.4}_{-0.9}$ and $Q_{\rm out} < 2.3$. Recall that broken emissivity profiles similar to the one found here is naturally expected when one suspects the black hole to be rapidly rotating and the corona to be compact[24,47,48]. The power-law index is found to be $1.69^{+0.02}_{-0.04}$ and the spin is constrained to

$$a = 0.82^{+0.05}_{-0.09} \text{ (90\% confidence)}.$$

Figure 2 in the main manuscript shows the ratio to this model after setting the normalisation of the disk and relativistic line component to zero, in order to highlight the contribution from these components. We also show in Extended Data Fig. 4 (b), the residuals to a single power-law before (top; $\chi^2/\nu = 782.0/416 = 1.88$) and after the addition of a DISKBB component (bottom; $\chi^2/\nu = 546.3/414 = 1.32$). An equally good fit can be achieved with the addition of a narrow (1 eV) Gaussian at 6.4 keV together with the relativistic line now having $Q_{\rm out} = 3$ ($\chi^2/\nu = 411.9/408 = 1.01$), and the spin value remains unchanged.

4.1.2. Baseline-reflection: As a final step in our assessment of the robustness of our results based on the *Chandra* data alone, we again replace the phenomenological combination of components described above with REFLIONX convolved with RelConv. A narrow (1ev) Gaussian is again added at 6.4 keV and we use the broken emissivity profile with $Q_{out} = 3$, as described above. Extended Data Fig. 5 (a) shows the fit to the time-averaged data and the right panel shows the extrapolated model. This model self-consistently accounts for the broad iron line and the soft-excess seen in this $z = 0.658$ quasar, in a manner similar to the canonical recipe for nearby sources. The best fit ($\chi^2/\nu = 439.6/409 = 1.07$) again yields constraints on the spin which are consistent with all others presented in this work, i.e.

$$a = 0.90^{+0.07}_{-0.15} \text{ (}3\sigma\text{ confidence)}.$$

We show the confidence contour for this model in Extended Data Fig. 3 (panel c; magenta contour). Extended Data Table 2 shows the parameters for this final model. As opposed to the phenomenological model described above, the additional narrow Gaussian at 6.4 keV is moderately statistically significant ($\Delta\chi^2 = -6.5$ for one more degree of freedom) when using the physically motivated model. As such, it appears that the narrow feature at 6.4 keV is indeed due to a combination of emission from distant materials as well as from the outer regions of the accretion disk.

4.2. Additional XMM-Newton data:

4.2.1. Baseline-simple: We now also consider our recent observation of RX J1131-1231 with *XMM-Newton*. A simple absorbed powerlaw model does not adequately describe the 0.3-10 keV range of the *XMM-Newton* EPIC-PN spectrum, with $\chi^2/\nu = 982.5/858 = 1.15$ (see Extended Data Fig. 6). Adding a disk component similar to the *Baseline-simple* model improves the fit significantly ($\Delta\chi^2/\Delta\nu = 65/2$) and an F-test shows that this extra component is required at greater than the 7σ level of confidence (F-test false alarm probability of 2×10^{-13}). The relatively high effective area of *XMM-Newton* at energies greater than 5 keV also allows for the clear detection of a break in the continuum. Indeed by allowing the powerlaw to break, we find $\chi^2/\nu = 899.9/854 = 1.05$, an improvement of $\Delta\chi^2/\Delta\nu = 17.7/2$ (F-test false alarm probability of 2.5×10^{-4}) over the fit without a break. Finally, the addition of a narrow Gaussian at $6.48^{+0.04}_{-0.03}\,\mathrm{keV}$ (rest frame) yields a best fit of $\chi^2/\nu = 862.4/852 = 1.01$ ($\Delta\chi^2/\Delta\nu = 37.5/2$; F-test false alarm probability of 1.3×10^{-8}) for this phenomenological combination of components. This final model suggests the presence of a soft excess which can again be characterised by a DISKBB component with $kT = 0.22 \pm 0.03\,\mathrm{keV}$, a powerlaw with an index $\Gamma = 1.83^{+0.07}_{-0.03}$ up to a break at $E_{\mathrm{break}} = 5.5^{+0.5}_{-2.2}\,\mathrm{keV}$, at which point the continuum hardens to $\Gamma = 1.28^{+0.33}_{-0.19}$. We show in Fig. 2 of the main manuscript the ratio to this $\Gamma = 1.83$ powerlaw.

Within the reflection-paradigm, this combination of a hardening at $\sim 10\,\mathrm{keV}$ (rest frame) together with a soft excess below $\sim 2\,\mathrm{keV}$ can be characterised as the beginning of the Compton hump and the blending of soft emission lines, respectively. To our knowledge, this is the first clear detection of a break associated with a Compton hump in a moderate-z quasar. In the following subsection, we proceed by modelling this spectrum within the context of relativistic reflection.

4.2.2. Baseline-reflection: We replace the phenomenological DISKBB component as well as the broken powerlaw with the *Baseline-reflection* model together with a narrow Gaussian (see Extended Data Fig. 6; b). This model is detailed in Extended Data Table 2. With a best fit of $\chi^2/\nu = 849.4/849 = 1.000$, it is clear that this self-consistent description provides a quality of fit that significantly outperforms even that of the phenomenological combination presented above.

We show in Extended Data Fig. 3 (panel c; green) the confidence range for the spin as obtained from the *XMM-Newton* data alone. The spin found here of

$$a = 0.64^{+0.33}_{-0.14}\ (3\sigma\ \mathrm{confidence}),$$

is again consistent with the range found during our analysis of the *Chandra* data.

It is clear from Extended Data Table 2 and Extended Data Figs. 5 and 6, that the ratio of the reflected flux to the powerlaw flux (the reflection fraction) is lower during the *XMM-Newton* observation, but the overall flux is higher. This trend of decreasing reflection fraction with increasing flux is often observed[55] in local AGN and within the reflection/light-bending interpretation[56] involves a corona whose height above the accretion disk is changing. In this scenario, a corona that is relatively close (a few r_{g}s) to the black hole will have more of its emission bent towards the disk, decreasing the fraction of the coronal emission that escapes to the observer, and thus increasing the observed reflection fraction. On the other hand, if the corona is further from the black hole so that its emission can be better characterised as being isotropic, then the total flux illuminating the disk decreases (more flux escapes to the observer) and so does the reflection fraction. Importantly, the behaviour seen here is not only fully consistent with the expectations of gravitational light-bending, but it also *requires* a system having a high spin, consistent with the value reported in this work. Similar behaviour has been reported for a number of AGN, most famously 1H0707-495[24] and MCG -6-30-15 [55] as well as stellar mass black holes[42].

4.3. Joint XMM-Newton and Chandra fit with *Baseline-reflection* model: It is clear from Extended Data Table 2 that, where the parameters are not expected to vary between observations, i.e. inclination, column density, and spin, the *XMM-Newton* observation yields consistent parameters to those obtained from the time-averaged *Chandra* data. In order to optimise the S/N and obtain a final estimate of the spin parameter of RX J1131-1231, we proceed by fitting both data sets simultaneously with the *Baseline-reflection* model, with the inclination, column density and spin tied between them. Extended Data Table 2 also details the various parameters for this final, joint fit and Figure 3 in the main manuscript (duplicated in Extended Data Fig. 3; panel c; black) shows the confidence contour obtained for the spin where we find a value of

$$a = 0.87^{+0.08}_{-0.15}\ (3\sigma \text{ confidence}),$$

based on the combined *Chandra* and *XMM-Newton* data.

5 No Evidence for Complex Absorption in RX J1131-1231:

To this point, we have based our modelling on the reflection paradigm and followed the well established methodology that has been applied to many local Seyferts. We note, however, that $\sim 50\%$ of these Seyferts[57] and a similar number of quasars[11] also display evidence for absorption by partially ionised, optically-thin material local to the accretion flow ("warm" absorbers; WAs).

Indeed, the canonical Seyfert galaxy, MCG-6-30-15, displays one of the most prominent relativistic lines known, and its X-ray spectrum also requires the presence of multiple absorption zones. Early spin measurements of MCG-6-30-15 (e.g. ref[8]) often strictly focused on data $\gtrsim 2\,\mathrm{keV}$, as the main effect of these warm absorbers are below this energy (e.g. ref[58]), notably the two strong edges of O VII and O VIII at $\sim 0.74\,\mathrm{keV}$ and $\sim 0.87\,\mathrm{keV}$, respectively [59] (note that for RX J1131-1231 at $z = 0.658$, this restricts the bulk effect of any possible WA to energies $\lesssim 0.5\,\mathrm{keV}$). However, subsequent detailed analyses accounting for the multizone warm absorber present in this source still obtained consistent spin measurements[52,55,60] and concluded that the relativistic iron line is robust to the precise details of the WA (e.g. [61]). Nonetheless, the presence of such a component in half of all quasars prompted us to investigate whether the residuals seen in RX J1131-1231 could be explained by WAs, and what effect the presence of a putative WA will have on our ability to constrain the spin of the black hole.

5.1. Partially Ionised Absorption:

5.1.1. Phenomenological modeling: We start by fitting the co-added spectra of Images-B and C with a model describing partially covering absorption by a partially ionised medium (zxipcf in XSPEC; ref[62]). The WA is characterised with an ionisation parameter $\xi_{\rm wa} = L/nr^2\,{\rm erg\,cm\,s^{-1}}$, where L is the ionising X-ray luminosity (${\rm erg\,s^{-1}}$), n the gas density (${\rm cm^{-3}}$), and r is the distance in centimeters between the source of ionising X-rays and the absorbing gas. The model also includes the covering fraction (cf) which defines the fraction of the source which is covered by the absorbing gas with a column density $N_{\rm H;wa}$, while the remaining (1-cf) flux from the source escapes directly to the observer. We initially allow the ionisation parameter, column density and covering fraction of zxipcf to be free, and apply this to a simple absorbed power-law model. In XSPEC terminology this model reads PHABS× (ZPHABS ×(ZXIPCF × (ZPOWERLAW))).

This model provided a goodness of fit equal to that of the power-law+DISKBB combination for both images (${\chi^2}_{\rm B}/\nu_{\rm B} = 426.1/355 = 1.20$ and ${\chi^2}_{\rm C}/\nu_{\rm C} = 263.6/247 = 1.07$ for Images-B and C respectively), meaning that it can account for the "soft-excess" to the same degree as the previous model using DISKBB. However, like the fit with a DISKBB, this model still cannot account for the residuals above $\sim 2\,{\rm keV}$. Adding a Gaussian, constrained to lie in the Fe K-shell energy range (6.4-6.97 ${\rm keV}$ local frame), to Image-B does not improve the fit; however, upon lifting this constraint we obtain an improvement (${\chi^2}_{\rm B}/\nu_{\rm B} = 414.0/352 = 1.18$). The Gaussian line has a centroid energy of $E_{\rm Gaussian} = 3.61^{+0.26}_{-0.24}\,{\rm keV}$ (local frame) and a width of $\sigma = 710^{+370}_{-570}\,{\rm eV}$. It is clear that such a broad line, with a centroid energy much lower than the 6.4 ${\rm keV}$ expected for neutral iron is a rather unphysical combination which is artificially mimicking a broad, relativistic line. Alternative scenarios such as Compton broadening aimed at explaining broad lines of this magnitude have been shown to not be a viable alternative in Seyfert galaxies[29]. As such, we replace the Gaussian with RelLine and constrain the energy to 6.4-6.97 ${\rm keV}$ as per usual. This model, with a WA, provides a better fit (${\chi^2}_{\rm B}/\nu_{\rm B} = 407.2/349 = 1.17$), and most importantly, models the residuals in a physically motivated manner. We note that adding a second zone does not improve the fits. Focusing on Image-C, we find that while the addition of a Gaussian does improve the fit (${\chi^2}_{\rm C}/\nu_{\rm C} = 241.0/244 = 0.99$), it is not statistically significant. Replacing this Gaussian with RelLine does remove clear systematic residuals and indeed increases the goodness of fit to ${\chi^2}_{\rm C}/\nu_{\rm C} = 234.1/241$ ($\chi^2_\nu = 0.97$).

The ionisation parameter of the putative WA is not well constrained for either image, with both cases resulting in upper limits of $\log_{10}\xi \lesssim 1.5$. It is clear that the WA is having the same affect as the phenomenological DISKBB model. However, the spin obtained via the relativistic line alone for Images-B and C are consistent with all other results presented here ($a_{\rm B} = 0.89^{+0.02}_{-0.09}$ and $a_{\rm C} = 0.8^{+0.09}_{-0.06}$ at the 90% confidence), and most importantly is still constrained to be high.

5.1.2. Baseline-reflection: As a broad relativistic Fe-$K\alpha$ line is naturally accompanied by other emission at lower energies, which can self-consistently account for the soft-excess, we proceed by reverting back to our *baseline-reflection* model (as detailed on Extended Data Table 1) in order to model the residuals above $\sim 2\,\mathrm{keV}$(observed frame) in both images. However, we now include an additional WA in order to investigate any possible effect on the results obtained with this model.

The addition of zxipcf to the *Baseline-reflection* model for the co-added Image-B data improves the quality of the fit by $\Delta\chi^2{}_{\mathrm{B}}/\Delta\nu_{\mathrm{B}} = -5.2/-3$ (final $\chi^2{}_{\mathrm{B}}/\nu_{\mathrm{B}} = 402.4/348 = 1.16$), i.e., this extra component is not statistically significant. Nonetheless, we note that this fit to Image-B yields $N_{\mathrm{H;wa;B}} = (1.4^{+5.0}_{-0.8}) \times 10^{22}\,\mathrm{cm}^{-2}$, $\log_{10}\xi_{\mathrm{wa;B}} < 2.1$ and $cf = 0.2^{+0.3}_{-0.1}$. All other parameters stay the same as those presented in Table S1, within the errors. As the addition of this extra component over the *baseline-reflection* model is not statistically significant, we also tried fixing $\log_{10}\xi_{\mathrm{wa;B}} = 2$, typical of both Seyferts like MCG-6-30-15 as well as Quasars such as PG 1309+355 (ref[63]). Again the improvement over a model without such absorption is barely significant at $\Delta\chi^2{}_{\mathrm{B}}/\Delta\nu_{\mathrm{B}} = -3.1/-2$; nonetheless, this fit again gives a low covering fraction ($cf < 0.27$) and the constraint on the spin remains essentially unchanged ($a = 0.91 \pm 0.05$) from that reported on Extended Data Tables 1. Freezing $\log_{10}\xi_{\mathrm{wa;B}} = 3$ or 1 does not change this conclusion nor does the addition of a second WA.

Adding a similar absorber to the *baseline-reflection* model for Image-C does not provide any improvement over that reported on Extended Data Table 1 and none of the WA parameters are constrained. We thus proceed by again freezing the ionisation to $\log_{10}\xi_{\mathrm{wa;B}} = 2$ and setting the column density to $N_{\mathrm{H;wa;C}} = 1 \times 10^{22}\,\mathrm{cm}^{-2}$ so as to obtain a rough limit on any potential covering fraction. This imposed WA provides a fit that is statistically similar to that shown in Extended Data Table 1 and sets a limit on the covering fraction of $cf \leq 0.12$. Again the spin remains unchanged.

We have also investigated the addition of a WA to the *baseline-reflection* model used in the time-resolved spectral analyses presented in § 3. We initially allowed the column density and covering fraction to vary between epochs but kept the ionisation parameter frozen at $\log_{10}\xi_{\mathrm{wa}} = 2$. This did not improve the fits. Neither did freezing the ionisation at $\log_{10}\xi_{\mathrm{wa}} = 3$, or allowing it to vary between epochs. In fact, the additional 54 or 81 free parameters, depending on whether $\log_{10}\xi_{\mathrm{wa}}$ was frozen or not, made the overall reduced χ^2 worse than that without this extra component. It is clear that the addition of a WA does not improve the quality of the fits nor does it affect the values for the spin obtained here. We therefore conclude that RX J1131-1231 does not require the presence of a WA on top of the self-consistent *baseline-reflection* model.

5.2. Neutral Absorption: We have also investigated the use of multiple neutral, partially covering absorption components, in addition to the fully covering neutral absorption included in all models, with the ZPCFABS model within XSPEC. Initially we restrict our consideration to Compton-thin absorption. First, we add an additional partially covering neutral absorber to the relativistic reflection model considered previously for the joint *Chandra* and *XMM-Newton* dataset. We obtain a best fit commensurate with that reported on Extended Data Table 2, with $\chi^2/\nu = 1279.2/1256 = 1.02$ and most importantly, a spin parameter tightly constrained to $a = 0.75^{+0.06}_{-0.09}$ (3σ); statistically similar to that reported on Extended Data Table 2. Second, we attempt to construct absorption-dominated models, but find that it is not possible to reproduce either the combined *Chandra* or the *XMM-Newton* data solely using reasonable combinations of such models, i.e. without any contribution from relativistic reflection. For the *Chandra* data, residuals associated with the broad iron line still persist, and it is not possible to account for the spectral curvature above $\sim$5 keV in the *XMM-Newton* data.

Finally, we relax the requirement that the absorbers are Compton-thin. However, we find this only influences the fit to the *XMM-Newton* data, where we find that a partially-covering ($cf = 0.27^{+0.12}_{-0.11}$), Compton-thick absorber ($N_{\mathrm{H}} = 1.68^{+1.75}_{-0.72} \times 10^{24}\ \mathrm{cm}^{-2}$) can successfully account for the high-energy excess in the *XMM-Newton* data. We therefore also include in this model a cold ($\xi = 1$), unblurred REFLIONX component aimed at simulating reprocessed emission from Compton-thick material far from the black hole. Nevertheless, when this model is applied to the joint *XMM-Newton* and *Chandra* dataset, with the partially covering absorber allowed to vary between the *XMM-Newton* and *Chandra* data, despite a visibly good fit to the *XMM-Newton* data above $\sim 5\,\mathrm{keV}$ now being obtained this model still provides a worse fit ($\Delta\chi^2 = 54.7$) than the *Baseline-reflection* model, and systematic residuals persist in the *Chandra* data between $\sim$1–5 keV. Although the best fit absorber for the *Chandra* data remains Compton-thin ($N_{\mathrm{H}} = 8.40^{+1.14}_{-0.97} \times 10^{22}\ \mathrm{cm}^{-2}$), a similar covering fraction is inferred ($cf = 0.31 \pm 0.03$). Given the known size of the X-ray emitting region ($\sim$10 r_{g}), determined independently by X-ray microlensing[20], such small covering fractions require a highly fine-tuned and *ad-hoc* geometry for the absorbing cloud. Furthermore, we stress that a scenario in which the spectral features are formed by absorprion/reprocessing by large, distant, distributed structures is also strongly at odds with the known size of the X-ray source.

42. Reis, R. C. et al. Evidence of Light-bending Effects and Its Implication for Spectral State Transitions. Astrophys. J. **763**, 48 (2013).

43. Brenneman, L. W. et al. The Spin of the Supermassive Black Hole in NGC 3783. Astrophys. J. **736**, 103 (2011).

44. Reis, R. C. et al. X-Ray Spectral Variability in NGC 3783. Astrophys. J. **745**, 93 (2012).

45. Popović, L. Č., Mediavilla, E. G. & Muñoz, J. A. The influence of microlensing on spectral line shapes generated by a relativistic accretion disc. Astron. Astrophys. **378**, 295–301 (2001).

46. Abajas, C., Mediavilla, E., Muñoz, J. A., Popović, L. Č. & Oscoz, A. The Influence of Gravitational Microlensing on the Broad Emission Lines of Quasars. Astrophys. J. **576**, 640–652 (2002).

47. Fabian, A. C. et al. On the determination of the spin of the black hole in Cyg X-1 from X-ray reflection spectra. Mon. Not. R. Astron. Soc. 3135 (2012).

48. Wilkins, D. R. & Fabian, A. C. Determination of the X-ray reflection emissivity profile of 1H 0707-495. Mon. Not. R. Astron. Soc. **414**, 1269–1277 (2011).

49. Ross, R. R. & Fabian, A. C. A comprehensive range of X-ray ionized-reflection models. Mon. Not. R. Astron. Soc. **358**, 211–216 (2005).

50. Fabian, A. C. & Vaughan, S. The iron line in MCG-6-30-15 from XMM-Newton: evidence for gravitational light bending? Mon. Not. R. Astron. Soc. **340**, L28–L32 (2003).

51. Fabian, A. C. et al. A long hard look at MCG-6-30-15 with XMM-Newton. Mon. Not. R. Astron. Soc. **335**, L1–L5 (2002).

52. Brenneman, L. W. & Reynolds, C. S. Constraining Black Hole Spin via X-Ray Spectroscopy. Astrophys. J. **652**, 1028–1043 (2006).

53. Hamann, F. & Ferland, G. The Chemical Evolution of QSOs and the Implications for Cosmology and Galaxy Formation. Astrophys. J. **418**, 11 (1993).

54. Iwamuro, F. et al. Fe II/Mg II Emission-Line Ratios of QSOs within $0 < z < 5.3$. Astrophys. J. **565**, 63–77 (2002).

55. Vaughan, S. & Fabian, A. C. A long hard look at MCG-6-30-15 with XMM-Newton- II. Detailed EPIC analysis and modelling. Mon. Not. R. Astron. Soc. **348**, 1415–1438 (2004).

56. Miniutti, G. & Fabian, A. C. A light bending model for the X-ray temporal and spectral properties of accreting black holes. Mon. Not. R. Astron. Soc. **349**, 1435–1448 (2004).

57. Reynolds, C. S. An X-ray spectral study of 24 type 1 active galactic nuclei. Mon. Not. R. Astron. Soc. **286**, 513–537 (1997).

58. Lee, J. C. et al. Revealing the Dusty Warm Absorber in MCG -6-30-15 with the Chandra High-Energy Transmission Grating. Astrophys. J. **554**, L13–L17 (2001).

59. Fabian, A. C. et al. ASCA observations of the warm absorber in MCG-6-30-15: The discovery of a change in column density. Publ. Astron. Soc. Jap. **46**, L59–L63 (1994).

60. Chiang, C.-Y. & Fabian, A. C. Modelling the broad-band spectra of MCG-6-30-15 with a relativistic reflection model. Mon. Not. R. Astron. Soc. **414**, 2345–2353 (2011).

61. Young, A. J. et al. A Chandra HETGS Spectral Study of the Iron K Bandpass in MCG -6-30-15: A Narrow View of the Broad Iron Line. Astrophys. J. **631**, 733–740 (2005).

62. Reeves, J. et al. On why the iron K-shell absorption in AGN is not a signature of the local warm/hot intergalactic medium. Mon. Not. R. Astron. Soc. **385**, L108–L112 (2008).

63. Ashton, C. E. et al. XMM-Newton observations of warm absorbers in PG quasars. Mon. Not. R. Astron. Soc. **355**, 73–81 (2004).